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RESEARCH MEMORANDUM

PRELIMINARY STUDY OF CIRCULATION IN AN APPARATUS SUITABLE FOR DETERMINING CORROSIVE EFFECTS OF HOT FLOWING LIQUIDS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY STUDY OF CIRCULATION IN AN APPARATUS SUITABLE FOR DETERMINING CORROSIVE EFFECTS OF HOT FLOWING LIQUIDS

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SUMMARY

A simple apparatus particularly applicable to the determination of the corrosive effects of flowing liquid metals on structural materials is described. In this apparatus, flow of the liquid medium at known velocities may be induced in toroidal shaped channels fabricated from the test structural material only, with no pump, valves, or flow meter required. A circulating velocity of 25 ft/sec has been obtained in preliminary tests and no basic limitation on increasing the speed was encountered.

INTRODUCTION

When testing a material for its resistance to corrosion by special liquids at high temperatures and high flow rates, it is desirable that the complete circulating system be composed of the test material only and contain no foreign materials which may dissolve in the liquid and affect the rate of corrosion. Additional important considerations are discussed below.

The construction of a pumping element from each test material for circulating the liquid may be costly and time consuming; hence, a method of circulating the fluid which does not involve the introduction of a pump element into the liquid stream would be desirable. The circulating test loop should be compact to require only a small amount of the test materials, some of which may be scarce. The test loop should be adaptable to the installation of a heating system for maintaining a difference in temperature between two sections of the loop to simulate the temperature differential that exists in some systems of practical interest in which the temperature difference may be a fundamental factor affecting the rate of corrosion.

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The purpose of this report is to describe a corrosion test apparatus which attempts to meet these requirements and some preliminary experiments on this equipment.

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DESCRIPTION OF APPARATUS

Circulating apparatus. - A schematic diagram of the system is shown in figure 1. A horizontal circular plate is attached at its center (by means of a bearing) to the crank pin of a vertical crankshaft. A compound parallelogram type of restraining mechanism, attached to the edge of the plate and to the supporting structure, maintains the plate in fixed orientation with respect to the mounting structure. Rotation of the crankshaft results in motion of the plate such that any point on its surface describes a circle with radius equal to the crank throw. The crankshaft is driven by a motor with a variable-speed transmission.

The test specimen, a length of tubing with its ends joined to form a toroid, is mounted on the circular plate. It is apparent from consideration of the geometry of the apparatus that as the crankshaft is rotated, the point on the toroid which is farthest from the center of rotation is on a straight line passing through the centers of the crankshaft and crank pin. If the toroid is partially filled with fluid a slug of fluid will be formed, the center of gravity of which will tend to approach the point of greatest radius due to centrifugal force. This point of greatest radius makes one revolution for every revolution of the crankshaft, and hence the fluid within the toroid will make one circuit of the toroid for every revolution of the crankshaft. The toroid on the other hand is constrained from rotating about the crankshaft by the parallelogram arms. The velocity of the fluid around the toroid is given by

$$V = 2\pi RN$$

where

V fluid velocity relative to toroid walls, (ft/sec)

R radius of toroid, (ft)

N crankshaft speed, revolutions per sec

An analysis of the forces involved in circulating the fluid is given in the appendix.

For high test speeds it is necessary that the apparatus be properly balanced and an adjustable counterweight was provided for this purpose.

A perspective drawing of the circulating apparatus with a corrosion specimen in place is shown in figure 2.

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Torodial test specimens. - No corrosion data have been obtained as yet; however, toroids with mean diameters of 15.5 inches have been fabricated of type 347 stainless-steel tubing having an outside diameter of 0.625 inch and 0.06-inch wall for proposed tests with molten sodium hydroxide. The dimensions of these toroids were determined by preliminary tests which are described later in the report.

Figure 3 is a photograph showing a typical toroid with the heating coil partially removed to show the thermocouples. Eight chromel-alumel thermocouples are spot welded at equidistant points about the circumference. The toroid is wrapped with beaded heater wire, Inconel ribbon radiation barrier, and asbestos tape. The heaters are wrapped in a manner such that one-half of the tube can be maintained at a temperature level different from the other half. Clamps, as shown, affix the wrapped toroid to the mounting plate. The toroid is filled with the test fluid, is sealed by means of a modified compression type fitting (made of the test material), and is then purged of air by successive evacuating and filling with a purified inert gas through the vent tube visible in the photograph. After a calculated minimum of air remains, the toroid is finally filled with inert gas at atmospheric pressure and sealed off by crimping and welding the vent tube.

RESULTS OF PRELIMINARY TESTS

It is shown in the appendix that circulation can be obtained when

$$\frac{R}{r} \leqq \frac{2C}{fR} \frac{\sin \frac{1}{2} \theta_L}{\theta_L} \tag{19}$$

where

R toroid loop radius

r toroid bore radius

C crank throw

θ_L angle subtended by liquid slug in loop

f effective friction coefficient; (this coefficient includes the drag contributions of surface friction and of pick up of the fluid left on the surface after passage of the slug)

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Preliminary tests were made, utilizing transparent plastic tubes, to check the effect of these variables and to obtain some numerical values for the limiting value of R/r.

Figure 4 is a photograph of the apparatus with one of the plastic toroids being installed. A high-speed flash lamp, synchronized with the crankshaft, was used to facilitate observation of the liquids in the transparent toroids when the apparatus was in operation.

Figure 5 is a photograph of a slug of water circulating at a linear velocity of 20 ft/sec in a plastic toroid, having a mean diameter of 15.5 inches. In the photograph the liquid is rotating in a counter-clockwise direction, and the head and tail of the circulating slug are indicated by arrows.

Effect of crank throw. - Provision was made to adjust the crank throw through a range of from 1 to 3.5 inches. It was found that the maximum diameter of toroid in which flow could be induced increased with increasing crank throw over the range obtainable, and therefore all tests discussed subsequently were run with the maximum crank arm of 3.5 inches. This observation is in agreement with equation (19) which shows that an increase in the limiting value of R/r is obtained by increasing C.

Effect of crankshaft speed. - In general, it was found necessary to accelerate the fluid slowly from a standstill to insure formation of a fluid slug. When first formed the slug had a long tail of fluid which did not completely fill the tube. The length of this tail was found to decrease as the rotational speed of the crankshaft was increased over the range permitted by the apparatus. It was further observed that, for fluids which wet the walls of the tube, the center of gravity of the circulating slug approached closer to the point of maximum centrifugal force (located at the intersection of the tube and a line projected through the centers of the crankshaft and crank pin) as the crankshaft speed was increased. The highest crankshaft rotative speed obtainable with the present apparatus resulted in a fluid velocity of 25 ft/sec.

Effect of loop radius to bore radius ratio. - Tests were made with plastic toroids, 40 percent full of water, for a range of bore diameters from 0.188 to 0.50 inch and mean diameters from about 6 to 24 inches.

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It was found that in all cases flow could easily be induced with loop to bore radius ratios up to about 36. Observation of equation (19) in the light of the constant value of limiting R/r obtained in these tests indicates that the effective friction coefficient f must be a function of R in order to compensate for the appearance of R in the right hand denominator.

Effect of fluid properties. - Tests were made with tubes filled to about 40 percent of capacity with the following liquids: carbon tetrachloride, acetylene tetrabromide, a mixture of hydrocarbons and a mercuric nitrate solution. Each of the latter two solutions was compounded to simulate both the density and viscosity of liquid sodium hydroxide at a temperature of 750° F.

Both the densities and viscosities of these fluids differed widely from those of water; however, the maximum loop-to-bore radius ratio in which flow could be induced was still about 36.

The above fluids wet the wall of the plastic tubing. Various toroids, about 40 percent full of mercury, which did not wet the tube wall, were tested and it was observed that the limiting loop to bore radius ratio was higher than 36 but less than 96.

Effect of filled volume. - Tests were made to determine the effect of varying the fraction of toroid volume occupied by the fluid. Toroids of 0.5 inch bore and 49 inch circumference were used with some of the fluids previously mentioned.

Slug flow was most easily induced when the fluid volume was equal to about 40 percent of the toroid volume. Reliable slug flow was obtained for fluid volumes from 10 to 50 percent of the toroid capacity. For fluid volumes less than 10 percent or greater than 50 percent of toroid capacity slug flow could not be induced.

ADDITIONAL REMARKS

Observation of the fluids flowing in the plastic toroids indicated that the liquid slug is very turbulent, due perhaps to secondary flow caused by the pressure differences about the periphery of the bore and to boundary layer phenomena at the leading and trailing ends of the fluid slug as it advances. Because of this turbulence, and because of the difficulty of measuring fluid temperatures without interrupting the flow, the relationship between the corrosion rates expected with the present apparatus, and that occurring with continuous flow in straight tubes is uncertain. It is believed, however, that the present apparatus will produce corrosion rates which are greater than those obtained with continuous flow in straight tubes.

SUMMARY OF RESULTS

The results of preliminary studies of fluid circulation in the described apparatus can be summarized as follows:

1. A liquid flow velocity of 25 ft/sec was obtained in the test loop at the top speed of the motor used in the present installation. No basic limitation to further increase in flow velocity was encountered in these tests.

2. Circulation in the toroid was obtained with loop radius to bore radius ratios up to 36 for a number of materials (water, carbon tetrachloride, acetylene tetrabromide, a mixture of hydrocarbons, and a mercuric nitrate solution). With mercury, circulation was obtained at values of the loop radius to bore radius ratio higher than 36 but not as high as 96. The length of the corresponding crank throw was $3\frac{1}{2}$ inches.

3. Increasing the crank throw of the apparatus was found to increase the tendency for circulation in agreement with conclusions arrived at from theoretical considerations.

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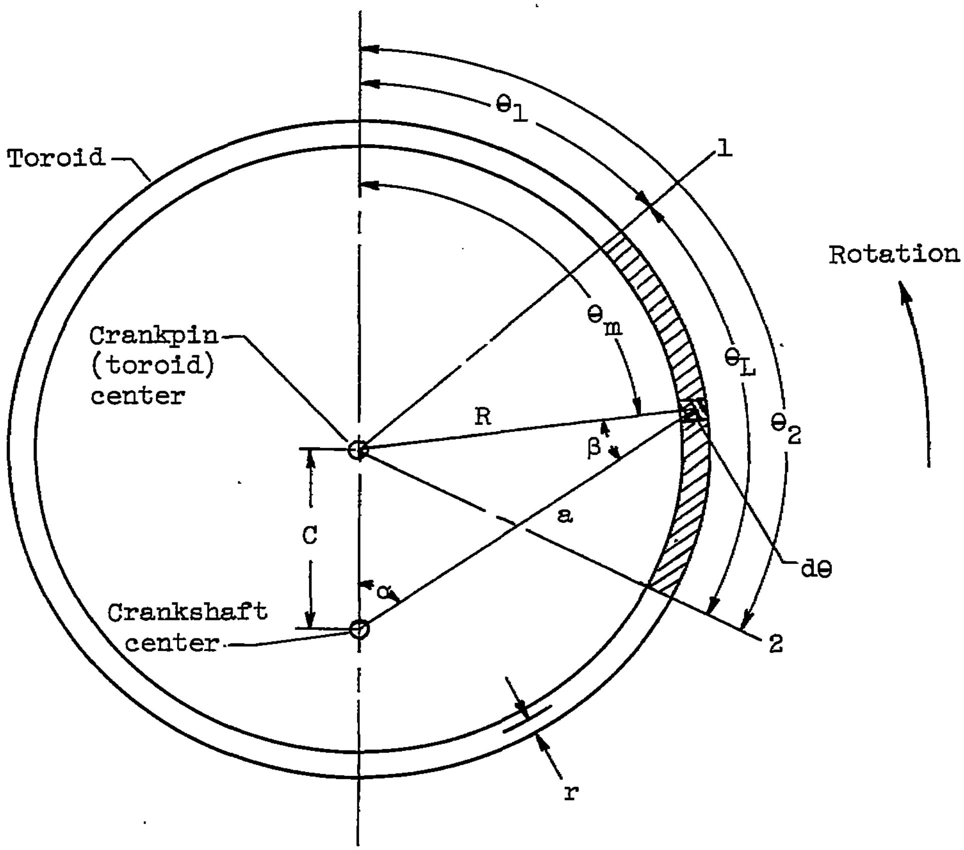
APPENDIX - DERIVATION OF RELATION FOR CIRCULATION IN TOROID



A	cross-sectional area of toroid bore, ft^2
a	distance from crankshaft center to slug element $d\theta$, ft
C	crank throw, ft
R	radius of toroid, ft
r	radius of toroid bore, ft
α	angular distance about crankshaft center measured from line through crankpin and crankshaft centers, radians

β angle between crankpin center and crankshaft center measured from slug element $d\theta$, radians

θ angular distance about crankpin center measured from line through crankpin and crankshaft centers, radians

θ_L angle subtended by fluid slug, $(\theta_2-\theta_1)$, radians

θ_m angle to midpoint of fluid slug, $\frac{(\theta_2+\theta_1)}{2}$, radians

ρ density of fluid, lb/ft^3

ω angular velocity, radians/sec

Subscripts:

1 pertaining to head of fluid slug

2 pertaining to tail of fluid slug

The centrifugal force dF on slug element $d\theta$ is given by

$$dF = AaR\rho\omega^2 d\theta \tag{1}$$

The component of dF tangent to the tube

$$dF_t = dF \sin \beta \tag{2}$$

From the diagram it is apparent that

$$\frac{\sin \alpha}{\sin \beta} = \frac{C}{R} \tag{3}$$

$$\sin \alpha = \frac{R}{a} \sin \theta \tag{4}$$

$$\sin \beta = \frac{C}{a} \sin \theta \tag{5}$$

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Substitution of equations (1) and (5) in (2) gives

$$dF_t = ACR\rho\omega^2 \sin\theta \, d\theta \tag{6}$$

from which

$$F_t = \int_{\theta_1}^{\theta_2} ACR\rho\omega^2 \sin\theta \, d\theta \tag{7}$$

or

$$F_t = ACR\rho\omega^2 \left[\cos\theta_1 - \cos\theta_2\right] \tag{8}$$

from the diagram it is seen that

$$\theta_L = (\theta_2 - \theta_1) \tag{9}$$

$$\theta_m = \frac{1}{2}(\theta_2 + \theta_1) \tag{10}$$

From equations (9) and (10)

$$\theta_1 = \frac{1}{2}(2\,\theta_m - \theta_L) \tag{11}$$

$$\theta_2 = \frac{1}{2}(2\,\theta_m + \theta_L) \tag{12}$$

By trigonometric addition and equations (11) and (12)

$$\cos\theta_1 = \cos\left(\theta_m - \frac{1}{2}\theta_L\right) = \cos\theta_m \cos\frac{1}{2}\theta_L + \sin\theta_m \sin\frac{1}{2}\theta_L \tag{13}$$

$$\cos\theta_2 = \cos\left(\theta_m + \frac{1}{2}\theta_L\right) = \cos\theta_m \cos\frac{1}{2}\theta_L - \sin\theta_m \sin\frac{1}{2}\theta_L \tag{14}$$

Substituting equations (13) and (14) in (8) gives

$$F_t = 2\ ACR\rho\omega^2 \sin\theta_m \sin\frac{1}{2}\theta_L \tag{15}$$

or

$$F_t = 2\pi\ Cr^2 \frac{V^2}{R} \rho \sin\theta_m \sin\frac{1}{2}\theta_L \tag{16}$$

For the fluid to circulate F_t must be equal to the frictional force F_d. The frictional force is given by

$$F_d = \rho V^2 f\ \pi\ r\ R\ \theta_L \tag{17}$$

where f is the effective friction coefficient. Equating equations (16) and (17) for circulation gives

$$\frac{R}{r} = \frac{2C \sin\theta_m \sin\frac{1}{2}\theta_L}{f\ R\ \theta_L} \tag{18}$$

Because of the complicated flow conditions in the toroid due to secondary flow caused by the bend in the tube and backflow of the fluid left on the surface after passage of the slug, the value of f cannot be determined by ordinary means. It is probably a function of the flow parameters and dimensions of the tube and may best be determined experimentally. The value of f can be computed from equation (18) and the observed value of θ_m.

The angle of the midpoint of the slug at which F_t is a maximum is obviously $\theta_m = \frac{\pi}{2}$ at which $\sin\theta_m = 1$. Thus, to obtain circulation

$$\frac{R}{r} \leq \frac{2C \sin\frac{1}{2}\theta_L}{f\ R\ \theta_L} \tag{19}$$

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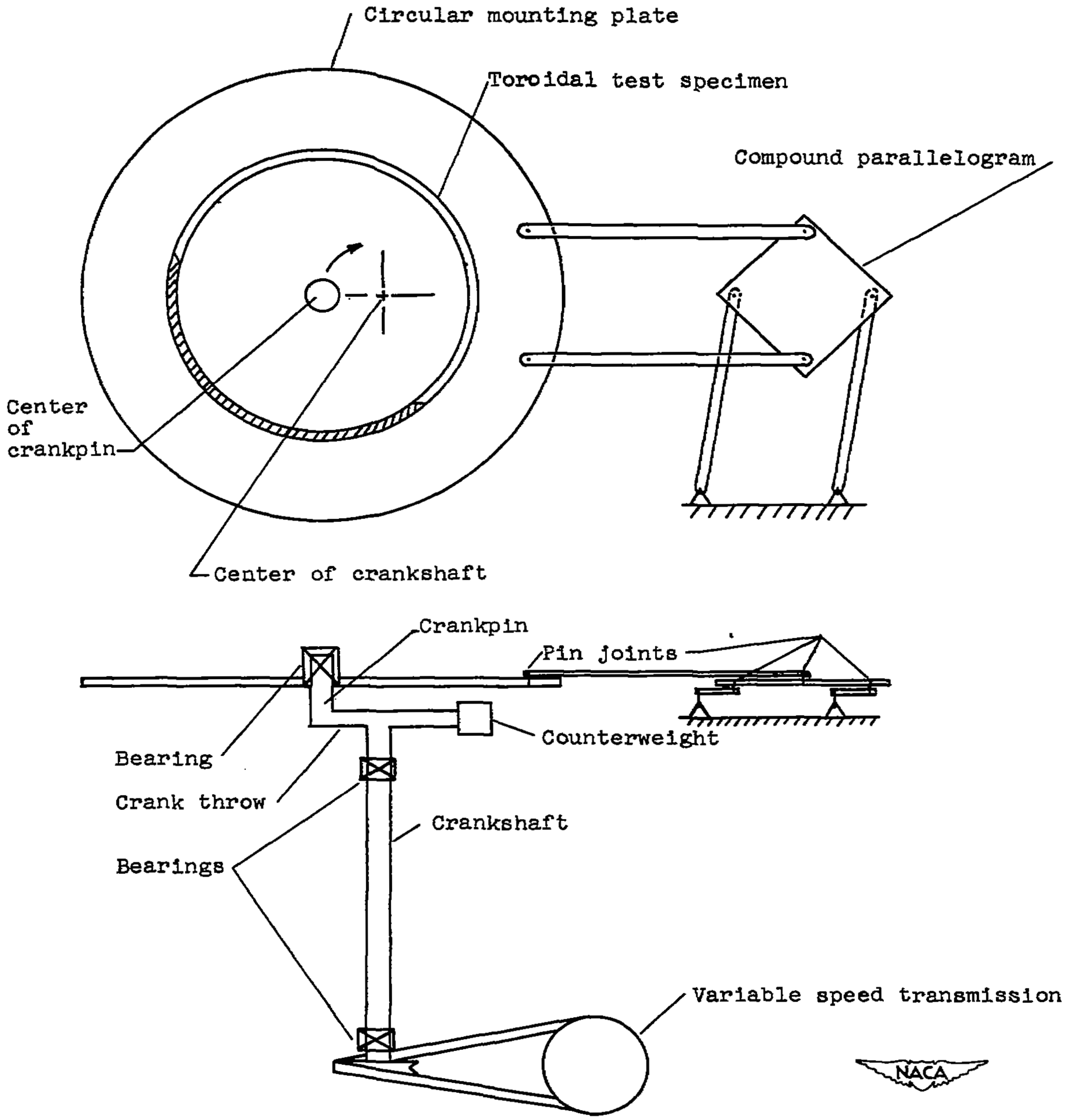

Figure 1. - Schematic diagram of circulating apparatus.

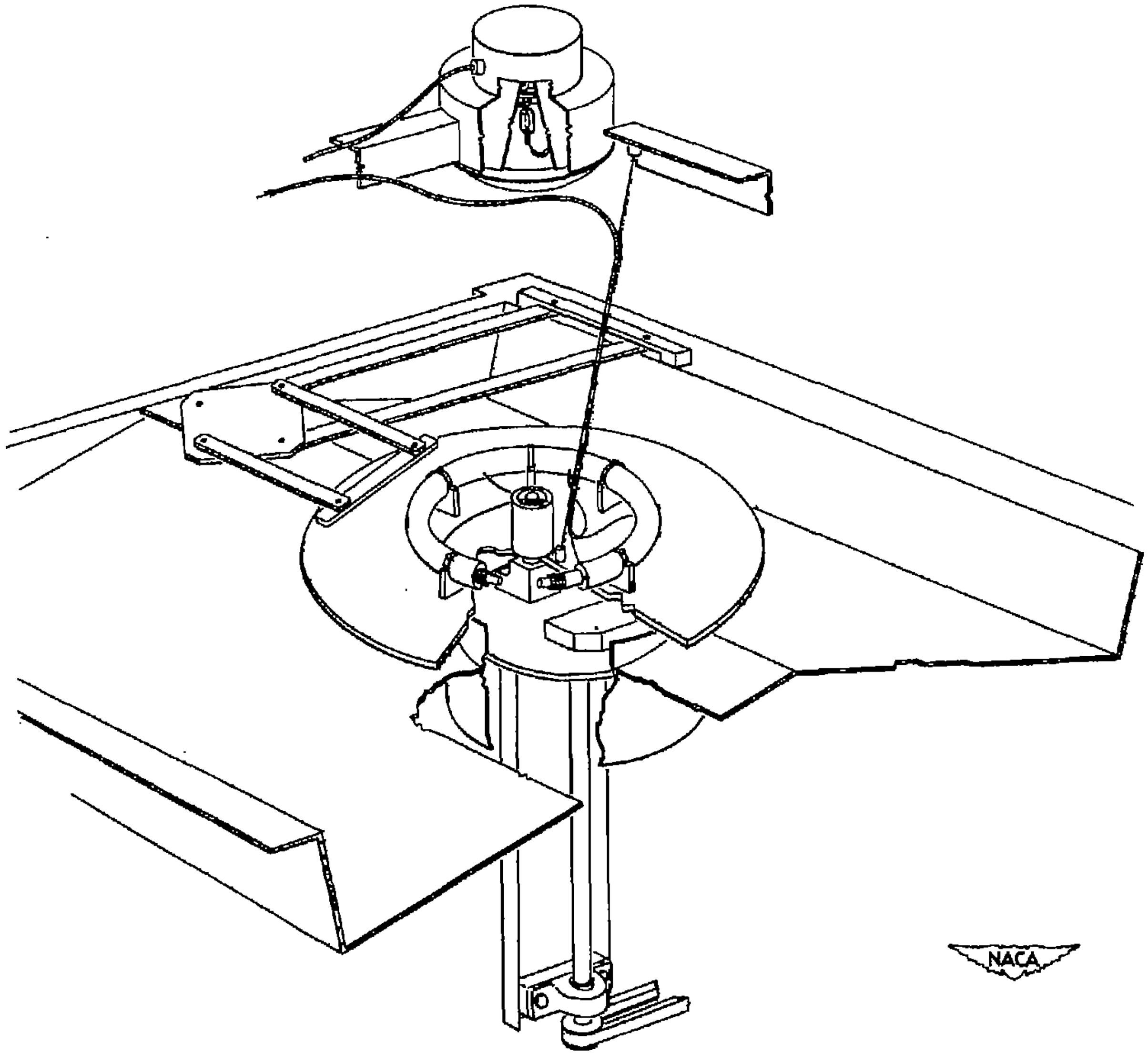

Figure 2. - Perspective drawing of circulating apparatus with corrosion specimen in place.

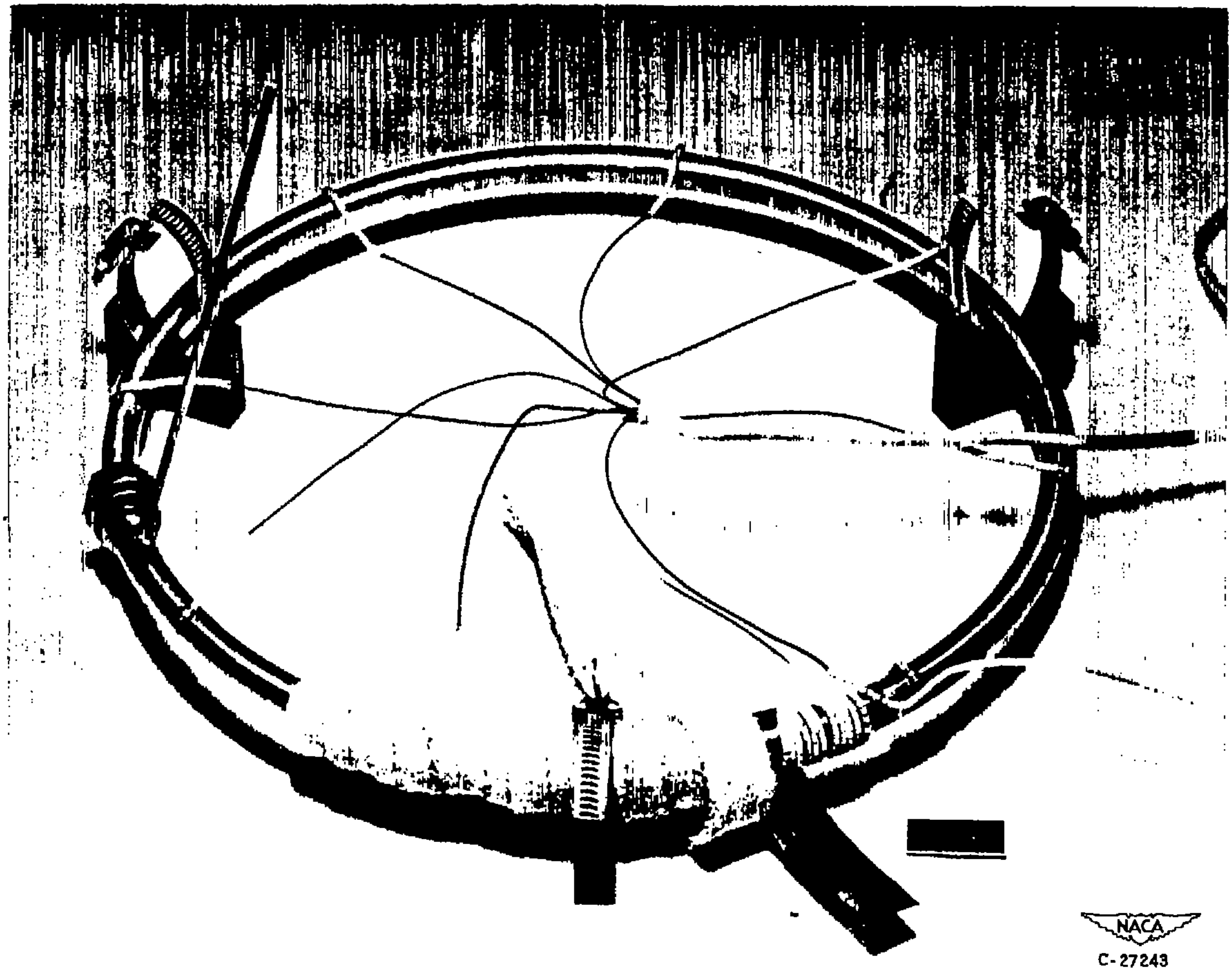

Figure 3. - Photograph of instrumented metal toroid.

Figure 4. - Photograph of circulating corrosion loop.

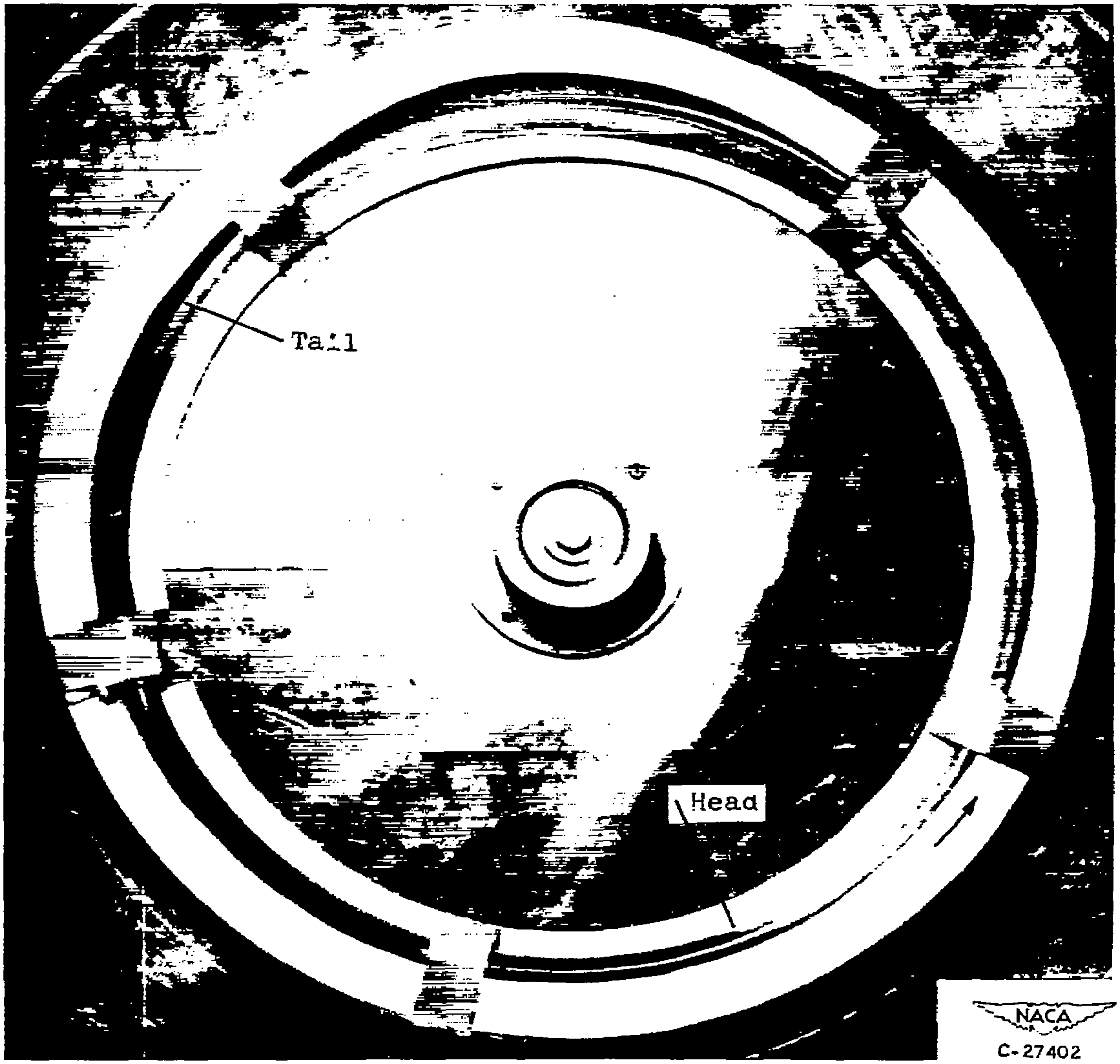

Figure 5. - Photograph of slug of water circulating in a plastic toroid of 15-1/2 inch mean diameter at a linear velocity of 20 feet per second.

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